

# Early Advanced LIGO binary neutron-star sky localization and parameter estimation

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**Abstract.** 2015 will see the first observations of Advanced LIGO and the start of the gravitational-wave (GW) advanced-detector era. One of the most promising sources for ground-based GW detectors are binary neutron-star (BNS) coalescences. In order to use any detections for astrophysics, we must understand the capabilities of our parameter-estimation analysis. By simulating the GWs from an astrophysically motivated population of BNSs, we examine the accuracy of parameter inferences in the early advanced-detector era. We find that sky location, which is important for electromagnetic follow-up, can be determined rapidly ( $\sim 5$  s), but that sky areas may be hundreds of square degrees. The degeneracy between component mass and spin means there is significant uncertainty for measurements of the individual masses and spins; however, the chirp mass is well measured (typically better than 0.1%).

## 1. Introduction

The advanced generation of ground-based gravitational-wave (GW) detectors, Advanced LIGO (aLIGO) [1] and Advanced Virgo (AdV) [2], begin operation soon: the first observing run (O1) of aLIGO is September 2015–January 2016 [3]. Binary neutron stars (BNSs) are a promising source [4].<sup>1</sup>

<sup>1</sup> Since submission, the first detection (of a binary black hole rather than a BNS), has been announced [5].

Analysis of a signal goes through several stages: detection, low-latency parameter estimation (PE), mid-latency PE and high-latency PE [6]. Each refines our understanding. To discover what we can learn about BNSs, a simulated astrophysically motivated population of BNS signals (component masses  $m_{1,2} \in [1.2, 1.6]M_{\odot}$ , isotropic spins with magnitudes  $a_{1,2} \in [0, 0.05]$ , and uniformly distributed in volume [7]) has been studied in an end-to-end analysis, with results reported in several publications. Singer *et al.* [7] studied the (low- and mid-latency) prospects for sky localization.<sup>2</sup> Berry *et al.* [8] repeated the analysis using more realistic noise (detector noise from the sixth science run of initial LIGO [9] recoloured to match the expected sensitivity of early aLIGO [10]), in contrast to ideal Gaussian noise. In addition to considering sky localization, Berry *et al.* [8] also investigated measurements of source distance and mass. The latter is influenced by spin, Farr *et al.* [11] completed the high-latency analysis including the effects of spin, considering all aspects of PE. We report results from these studies for O1 PE; further technical details are in the papers themselves.

## 2. Sky localization

Sky localization can be computed at low-latency by BAYESTAR [12] or at mid- to high-latency by LALINFERENCE [13].<sup>3</sup> Both are fully Bayesian PE codes; BAYESTAR uses the output of the detection pipeline, while LALINFERENCE matches GW templates to the measured detector strain [14]. Computing templates is computationally expensive; mid-latency PE is done with (non-spinning) TaylorF2 and high-latency PE is done with (fully spin-precessing) SpinTaylorT4. Both are inspiral-only post-Newtonian waveforms [15]. BAYESTAR takes a median time of 4.5 s to calculate the location [12]; the median times for the non-spinning and spinning LALINFERENCE analyses to collect 2000 posterior samples are  $\sim 5.7 \times 10^4$  s [8] and  $\sim 9.2 \times 10^5$  s [11] respectively.

Despite their differences, BAYESTAR and LALINFERENCE produce consistent results for a two-detector network.<sup>4</sup> The inclusion of spin in PE does not change sky localization for this slowly spinning population (the same may not be true for rapidly spinning black holes). At a constant signal-to-noise ratio (SNR)  $\varrho$ , there is also a negligible difference between results from Gaussian and recoloured noise. The scaling of the 50% credible region  $\text{CR}_{0.5}$  and 90% credible region  $\text{CR}_{0.9}$  with SNR is shown in Fig. 1. Assuming a detection threshold of a false alarm rate of  $10^{-2} \text{ yr}^{-1}$  ( $\varrho \gtrsim 10\text{--}12$ ), the median  $\text{CR}_{0.5}$  ( $\text{CR}_{0.9}$ ) is  $170 \text{ deg}^2$  ( $690 \text{ deg}^2$ ) using BAYESTAR and  $150 \text{ deg}^2$  ( $630 \text{ deg}^2$ ) using LALINFERENCE; switching to a threshold of  $\varrho \geq 12$  [3], these become  $140 \text{ deg}^2$  ( $520 \text{ deg}^2$ ) and  $120 \text{ deg}^2$  ( $480 \text{ deg}^2$ ) respectively [8].

## 3. Mass and spin

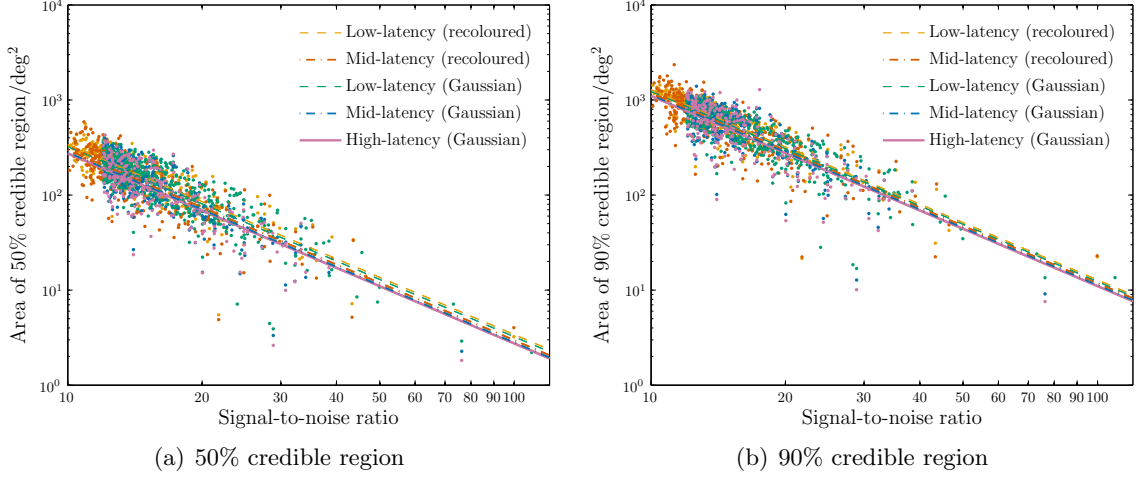
The first estimates for the component masses  $m_{1,2}$  come from the detection pipeline, here GSTLAL [16]. Full posteriors are constructed by LALINFERENCE. The degeneracy between mass and spin complicates measurements. Excluding spins (as in the mid-latency analysis) means we can miss the true parameter values. Allowing spins to vary over the full (black hole) range of  $a_{1,2} \in [0, 1]$  (as in the high-latency analysis) and including precession ensures we cover the true value, but potentially means that we consider spin values not found in nature: here, the spins are  $a_{1,2} < 0.05$ , but we will not know the true distribution in practice.

The chirp mass  $\mathcal{M} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$  is the best measured mass parameter. Fig. 2(a) shows the offset between chirp-mass estimates (maximum likelihood values for GSTLAL and posterior means for LALINFERENCE) and the true values. All methods produce accurate results (offsets  $< 0.5\%$ ) and there is no noticeable difference between recoloured and Gaussian noise. The mid-latency offsets are smaller than the high-latency ones, because our BNSs are slowly

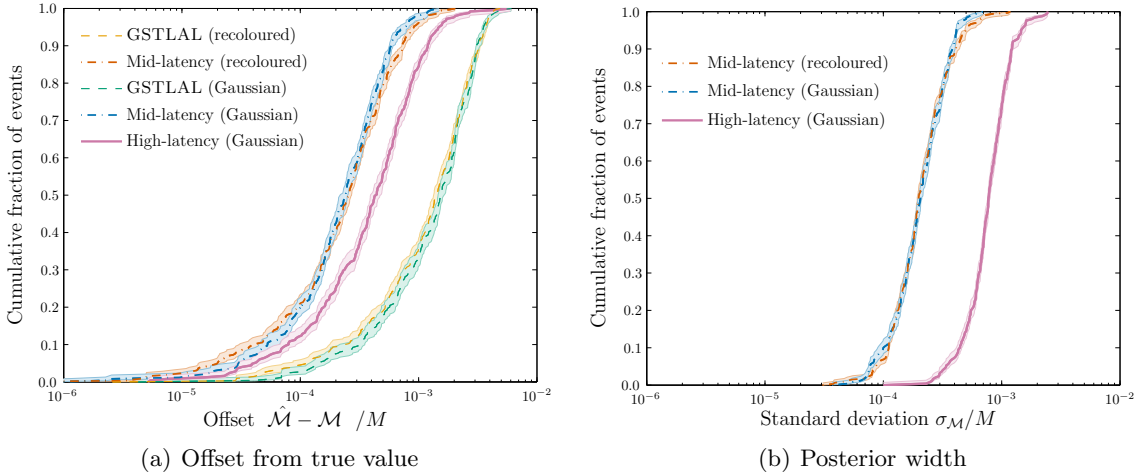
<sup>2</sup> Singer *et al.* [7] also considered the second observing run (O2), with AdV joining the network.

<sup>3</sup> Part of the LIGO Algorithm Library (LAL) available from [www.lsc-group.phys.uwm.edu/lal](http://www.lsc-group.phys.uwm.edu/lal).

<sup>4</sup> This is not the case in a three-detector network if there is not a trigger from all the detectors [7, 12].



**Figure 1.** Sky localization versus SNR for the low-latency BAYESTAR, the mid-latency (non-spinning) LALINFERENCE and the high-latency (spinning) LALINFERENCE analyses [7, 8, 11]. Individual results are indicated by points and lines indicate best fits assuming  $\text{CR}_p \propto \varrho^{-2}$ ; these are  $\text{CR}_{0.5} \approx (2.84 \times 10^4) \varrho^{-2} \text{ deg}^2$  and  $\text{CR}_{0.9} \approx (1.14 \times 10^5) \varrho^{-2} \text{ deg}^2$  across the range considered.



**Figure 2.** Cumulative fractions of events with (a) offsets in chirp-mass estimates and (b) posterior standard deviations smaller than the abscissa value [8, 11]. The offset is the difference between the true value  $\mathcal{M}_*$  and maximum likelihood value from GSTLAL or the posterior mean from (mid- or high-latency) LALINFERENCE. The shaded areas are the 68% confidence intervals on the cumulative distributions.

spinning (which need not be the case in reality). However, the mid-latency offsets are more statistically significant. The mean values of  $(\hat{\mathcal{M}} - \mathcal{M})^2 / \sigma_{\mathcal{M}}^2$ , where  $\sigma_{\mathcal{M}}$  is the posterior standard deviation, are 5.5, 5.1 and 0.7 for the recoloured non-spinning, Gaussian non-spinning and Gaussian spinning analyses respectively. Ignoring spin yields posteriors that are too narrow [8], the distribution of  $\sigma_{\mathcal{M}}$  is shown in Fig. 2(b) [11]; the median values of  $\sigma_{\mathcal{M}}$  are  $2.0 \times 10^{-4} M_{\odot}$ ,  $2.1 \times 10^{-4} M_{\odot}$  and  $7.7 \times 10^{-4} M_{\odot}$  for the recoloured non-spinning, Gaussian non-spinning and Gaussian spinning analyses respectively.

Measurements of other mass parameters, such as the mass ratio  $q = m_2/m_1$  ( $0 < q \leq 1$ ) or  $m_{1,2}$ , are less precise, and the degeneracy with spin is more pronounced [11, 14]: the median 50%

(90%) credible interval for  $q$  is 0.29 (0.59). For our population of low-spin BNSs, the spins are not well measured and have large uncertainties. None of the events have a 50% upper credible bound less than 0.1; the median 50% (90%) upper credible bound is 0.30 (0.70) for  $a_1$  (the dominant spin) and 0.42 (0.86) for  $a_2$ . Low spin values are preferred, but spin magnitudes can only be weakly constrained.

#### 4. Summary

O1 marks the beginning of the advanced-detector era. As time progresses, sensitivities improve and further detectors (AdV, LIGO-India [17] and KAGRA [18]) come online, the prospects for detection and PE will become better [7, 19, 20]. For BNSs, chirp mass is always well measured, but sky localization and spins are more uncertain.

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